XMM-Newton Observations of Unidentified Gamma-Ray Objects

- New Results in X-ray Astronomy, MSSL, 11th July 2006 -

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Gamma Ray Sources ID History

**SAS-2 (1972-1973):** 3 γ-ray sources detected, 2 identified

**COS-B (1975-1982):** 5 γ-ray sources detected, 3 identified

**GRO (1991-2000):** 271 γ-ray sources detected, 96 identified
The majority of the 3EG gamma-ray objects are still unidentified.

≈ 50% of high-latitude UGOs are identified, mostly associated with AGNs.

≈ 10% of low-latitude UGOs are identified, mostly associated with PSRs.
Possible IDs of Galactic UGOs

- The nature of low-latitude UGOs is unclear
- Candidates: SNRs, MicroQuasars, X-ray Binaries, Pulsars, Undiscovered

**MicroQuasars:**
- 3EG J1824-1514 (Mc Swain et al. 2004)
- 3EG J0241+6103 (Casares et al. 2005)
- 3EG J1639-4702 (Combi 2004) - ?

**Pulsars (?)**:
- 3EG J0222+4253 (Kuiper et al. 2002)
- 3EG J1048-5840 (Kaspi et al. 2000)
- 3EG J2021+3716 (Roberts et al. 2002)
- 3EG J2227+6122 (Halpern et al. 2001)
- 3EG J1420-6038 (D'Amico et al. 2001)
- 3EG J1837-0606 (D'Amico et al. 2001)
- 3EG J1013-5915 (Camilo et al. 2001)

**X-ray Binaries (?)**:
- 3EG J0634+0521 (Kaaret et al. 2000)
- 3EG J0542+2610 (Romero et al. 2001)
UGOs-PSRs connection

- PSRs are still the most likely counterparts to low-latitude UGOs
- Unfortunately, ID via gamma-ray timing is difficult:
  - Less Photons hamper blind searches via FFT
  - Lack of a reference period for light curve folding
  - Large Error Boxes $\Rightarrow$ Bad Timing accuracy
  - Uncertain source position ($< 1$ deg) $\Rightarrow$ $\Delta t$ (ms) $\sim 2.3$ $\Delta r''$
  - Uncertain correction to SSB

- Step-by-Step Multi-Wavelength approach is the only way
  - Search for possible X-ray counterparts
  - Optical identification of possible X-ray counterparts
  - Select X-ray sources with no (bright) optical counterpart, supposed to be Isolated Neutron Stars (INSs)
“The Geminga Approach”

- EINSTEIN/IPC mapping of the COS-B error box → X-ray counterpart
- EINSTEIN/HRI follow-up → Better Position
- Optical counterpart G" detected with the CFHT
- $L_{\gamma}/L_{\chi} \approx 1000 + L_{\chi}/L_{\text{opt}} \approx 1000$ ~ Vela Pulsar → INS
- Discovery of X-ray and γ-ray pulsations (237 ms) with ROSAT and GRO
3EG J0616-3310 & 3EG J1249-8330

- Pilot project carried out on two unidentified EGRET sources
  - Not too low gal lat to avoid galactic plane confusion
  - Not too high gal lat to minimize AGN contamination

- No radio counterparts

- Relatively bright: \( F_{\gamma} (>100 \text{ Mev}) \sim 13-20 \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1} \)
- Pulsar-like spectral shape: photon index \( \Gamma \sim 2.1 \)
- No evidence for gamma-ray variability
- Good Positioning \( \sim 0.65 \) degrees radius
X-ray Observations

• X-ray coverage of the two EGRET error boxes with XMM

• 4xEPIC pointings (~10 ks) per EGRET error box

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Rev.</th>
<th>Date</th>
<th>Pointing Coordinates</th>
<th>Exposure Time (ks)</th>
<th>N_H (10^{20} cm^{-2})</th>
<th>Detected Sources</th>
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<tbody>
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<td>06 17 47.1</td>
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<td>12 57 53.1</td>
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<td>−83 15 01.9</td>
<td>8.3</td>
<td>12.7</td>
</tr>
</tbody>
</table>

• Problems with pointing #7 due to high particle background

• Observations described in La Palombara et al. (2004); La Palombara, Caraveo, Mignani et al. (2005)
X-ray Data Analysis

- **X-ray data reduction** using the Standard Analysys Software (SAS)
  - Hot, flickering pixels, bad columns removed
  - Cosmic rays cleaning
  - Rejection of Time Intervals affected by high background
  - Selection of Good Time Intervals (GTI)
  - Exposure maps generate to account for QE, vignetting, exposure

- **X-ray Catalogue production**
  - EPIC PN+MOS1,2 event files merged to increase S/N (spatial binning 4.35")
  - X-ray Source Extraction in 2 Coarse + 5 Fine energy bands
  - Minimum Detection Likelihood: \( -\ln P > 8.5 \) in at least one energy band

  3EG 0616-3310: 146 X-ray sources down to \( F_{(0.5-2 \text{ Kev})} \sim 4 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \)

  3EG 1249-8330: 148 X-ray sources down to \( F_{(0.5-2 \text{ Kev})} \sim 4 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \)

- **X-ray Spectral Analysis**
  - The short exposure time does not yield enough counts for spectral fitting
  - Spectral information from the Hardness Ratios (HRs) over 7 energy bands
  - Measured HRs compared with simulated HRs for two spectral models: thermal bremsstrahlung \( (kT=0.5, 1, 2, 5) \) and power-law \( (\Gamma=1, 1.5, 2, 2.5) \)
Optical Observations

• Optical (BVRI) coverage with the 4x2 CCDs ESO 2.2m/WFI

• Additional BRI with GSC2.3 and JHK with 2MASS

<table>
<thead>
<tr>
<th>Date (dd.mm.yyyy)</th>
<th>Obs. ID</th>
<th>Filter Name</th>
<th>Num. Frames</th>
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<th>Average Seeing</th>
<th>Average Airmass</th>
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<td>2000.0</td>
<td>0.89</td>
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</tbody>
</table>

• (WFIx5)x4x4 pointings per EGRET error box (FOV ≈ 0.5x0.5 deg ≈ EPIC)

• Observations executed in Service Mode

• Not all pointings completed due to bad weather and scheduling constraints

• Error box of 3EG 1249-8330 poorly covered
Optical Data Analysis

- **Optical data reduction** with the THELI pipeline:
  - Basic Reduction (chip by chip on parallel CPUs)
  - Astrometric Calibration → Distorsion Map → Distorsion Correction
  - Image Stacking, CR rejection
  - Exposure Map Correction
  - Photometric Calibration

- **Catalogue production** using tools developed in the ESO Imaging Survey
  - Object Extraction → Single-Bands Catalogues
  - Multi-Band WFI Catalogues
  - Multi-Band WFI + 2MASS and GSC2

<table>
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<tr>
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<tr>
<td>8</td>
<td>15578</td>
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</table>
red = 0.3-1 keV
green = 1-3 keV
blue = 3-10 keV

red = R band
green = V band
blue = B band

XMM/EPIC

ESO2.2m/WFI

33 arcmin
The Strategy

- **Automatic Optical Classification**
  - Model SEDs library (stars, galaxies)
  - Convolution with band response → Simulated magnitudes
  - Interstellar Extinction evaluation (Schlegel maps)
  - Simulated vs Observed magnitudes → Optical Classification

- **X-ray vs Optical Multi-Band Catalogues Matching**

- **X-ray Source Classification**
  - \( F_x / F_{opt} \) → Distinctive of X-ray Source Class
  - HRs → Distinctive of X-ray Source Class
  - X-rays + Optical Classifications
  - Information passed to a Decision -Tree Algorithm

← Still to be fine-tuned
X-ray/Optical Cross-Correlations

<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Detected Sources</th>
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<td>3</td>
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<td>27</td>
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<tr>
<td>Total</td>
<td>146</td>
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<table>
<thead>
<tr>
<th>X-ray sources with counterpart</th>
<th>Candidate Counterparts</th>
<th>Reliability (1-P)</th>
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<tr>
<td>23</td>
<td>26</td>
<td>84 %</td>
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<tr>
<td>30</td>
<td>46</td>
<td>76 %</td>
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<tr>
<td>25</td>
<td>41</td>
<td>82 %</td>
</tr>
<tr>
<td>24</td>
<td>40</td>
<td>70 %</td>
</tr>
<tr>
<td>Total</td>
<td>102</td>
<td>153</td>
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</tbody>
</table>

Optical coverage less deep for 3EG1249-8330 than for 3EG 0616-3310

\[ P = 1 - e^{-\pi r^2 \mu} \]

\( r = \text{cross-correlation radius} = 5'' \)

\( \mu = \text{objects surface density per sq. degree} \)

16% < P < 30% → chancce coincidence contamination significant
The $F_x/F_{\text{opt}}$ ratio Classification Scheme

$$\frac{f_{X,XMM}}{f_B} = \frac{f_{X,Hamburg-RASS}}{f_B} \times \frac{f_{0.3-10,PL}}{f_{0.1-2.4,MOD}}.$$ 

CR-Flux conversion

$$\frac{f_B}{f_{BJ}} = \frac{f_{B,Vega}}{f_{BJ,Vega}} \times 10^{-\frac{(B-B_J)/2.5}{2.5}} = 0.822 \times 10^{-\frac{(B-B_J)/2.5}{2.5}}.$$ 

Flux conversion

<table>
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<tr>
<th>Obs. ID</th>
<th>Stars</th>
<th>WDs</th>
<th>CVs</th>
<th>Galaxies</th>
<th>Clusters</th>
<th>AGN</th>
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<td>+0.74±2.65</td>
<td>-1.33±1.31</td>
<td>-0.81±1.72</td>
<td>-0.13±1.91</td>
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<td>2</td>
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<td>0---1.71</td>
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<tr>
<td>4</td>
<td>-0.32±0.39</td>
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<tr>
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<tr>
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<td>7</td>
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<table>
<thead>
<tr>
<th>Obs. ID</th>
<th>Stars</th>
<th>WDs</th>
<th>CVs</th>
<th>Galaxies</th>
<th>Clusters</th>
<th>AGN</th>
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<td>-0.07±0.55</td>
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<td>-0.90±1.54</td>
<td>-0.42±1.95</td>
<td>-0.49±2.22</td>
<td>-0.37±1.84</td>
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</table>
Candidates Selection

- 125 X-ray sources with no optical counterpart selected. "Cesarean Cut" approach

- 9 X-ray sources with $F_x/F_{opt} > 100$

- $F_x/F_{opt}$ $\rightarrow$ no stars, no AGNs, no galaxies, no XRBs $\rightarrow$ hot stars (i.e. possible NSs)

- 8 X-ray sources with softer spectra, i.e. $KT<0.5$ keV and/or detected $<1$ keV only

- Possible Geminga-like INS candidates
Summary

- **3EG 0616-3310:**
  - About 30% have no optical counterpart down to V~24.5
  - 8 X-ray sources with Fx/Fopt > 100
  - 5 X-ray sources with a soft thermal spectrum
  - One X-ray source with both Fx/Fopt > 100 and a soft thermal spectrum

- **3EG 1249-8330:**
  - About 55% have no optical counterpart down to V~24.5
  - 1 X-ray source with Fx/Fopt > 100
  - 3 X-ray sources with a soft thermal spectrum

- Best candidates sorted according to Fx/Fopt
  - XMMU J061429.8-333225 for 3EG 0616-3310
  - XMMU J124642.5-832212 for 3EG 1249-8330


- Deep follow-up XMM investigation of UGO candidate counterparts in progress (timing, spectroscopy)
Future Work (i)

- **Extend the work to other selected EGRET UGOs**
  - Large program → More targets → More data → More efficiency

- **Exploit public X-ray archives and catalogues with their built-in XIDs**
  - X-ray pointings may easily overlap partially but not cover completely a whole EGRET error box
  - Selection by instrument mode to maximize FOV reduces the useful data set

- **Exploit public optical archives (e.g. ESO, CADC)**
  - Probability of finding optical data which (by chance) overlap with an X-ray field which (by chance) overlap with an EGRET error box is likely very small
  - Color coverage, critical for object classification, may not be adequate
  - FOVs of optical imaging devices is generally small (< 10x10 arcmin)

- **Exploit existing public CCD surveys (e.g. the SDSS)**
  - Sky coverage limited to selected sky areas
Future Work (ii)

- **Exploit new/future wide field optical/IR facilities**
  - MegaCam@CFHT, a 5x8 CCDs 1x1 deg optical/IR imaging camera
  - VST, a 2.5m ESO survey telescope equipped with the 4x8 CCDs 1x1 deg ΩCam (to be commissioned by Q4 2006)
  - VISTA, a 4m UK/ESO survey telescope with a 4x4 chip 1x1 deg IR detectors array (to be commissioned by Q2 2007)
  - ≈ 4x WFI

- **Improve data processing/analysis**
  - Data processing with parallel CPUs on Beowulf-like clusters
  - Smarter automatic classification algorithms (self learning by training sets)
Future Work (iii)

- The 3rd GRO/EGRET catalogue is still the reference
- No High Energy Gamma-ray coverage currently flying
- Wait for upcoming gamma-ray satellites

- **AGILE** (Astrorivelatore Gamma ad Immagini LEggero)
  - To be launched in 2006
  - 0.3° positioning, 60 deg f.o.v., sensitivity ≈ GRO/EGRET

- **GLAST** (Gamma-ray Large Area Space Telescope)
  - To be launched by Q3 2007
  - 0.15° positioning, 2.5 sr f.o.v., sensitivity: x50 GRO/EGRET

- Better statistics → improved timing and spectral analysis
- Better positioning → XMM follow-ups, one pointing only
  - x4 more efficient OR x2 deeper
  - VLT follow-ups, tighter Fx/Fopt
- More straight UGO identification
Conclusions

• Multiwavelength coverage of UGO EGRET error boxes is a valid identification strategy.
• UGO identification is one of the major goals of next years' high energy astrophysics.